Experimental Verification of Correlation-Based Wavefront Sensing

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Adaptive Optics (AO) systems provide real-time correction of phase aberrations using measurements of the wavefront slope. Most AO systems use a point source and an estimation algorithm for the wavefront sensor (WFS) (hereafter, "Correlation"), a method called centroiding. The alternative, Correlation-Based WFS, allows two important improvements to this scenario. First, Correlation is a more robust algorithm, producing higher accuracy, especially under changing conditions such as background and spot shape; and a much lower noise level. Second, Correlation can work with subimages of an extended target, greatly broadening the range of scenarios in which AO systems can function. This enables the use of AO to correct aberrations such as those on a lightweight optic or atmospheric turbulence in a remote imaging system.

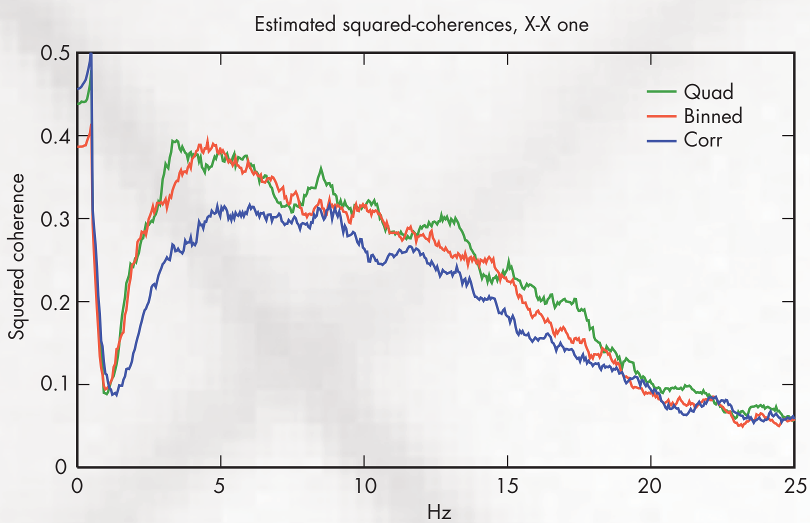

Figure 1. Temporal squared-coherence of slope measurements in closed-loop LGS operation of the Lick AO system.

Project Goals

Our two major goals are: to demonstrate experimentally that Correlation provides better performance than centroiding for the WFS, and to determine system requirements for AO operation for remote imaging, *e.g.*, frame rates, light levels, and availability of scenes.

Relevance to LLNL Mission

AO remote imaging is important for national security applications. This project will further extend LLNL capabilities in this area.

FY2004 Accomplishments and Results

We have demonstrated for both the Lick Observatory Laser Guide Star (LGS) AO system and the Solid State Heat Capacity Laser (SSHCL) AO system that Correlation can improve performance.

For Lick, the Correlation algorithm provides more stable gain with equivalent noise to the current algorithms, enabling improved correction. Figure 1 shows temporal coherence between neighboring WFS measurements of the residual phase aberration in closed-loop operation. As the AO correction of the phase improves, neighboring measurements of the residual phase become less coherent. The Correlation algorithm produces better correction than the centroiding methods currently in use.

For SSHCL, the centroiding algorithm is significantly biased by deformations in spots on the WFS and background scatter. Correlation is unbiased, and as an extra benefit provides a three to four times reduction in mean-squared-error due to noise. Figure 2 shows the temporal power spectra in open-loop WFS measurements of the phase. Both algorithms measure the same amount of signal power at low temporal frequencies. However, Correlation has a much lower noise floor than centroiding, as is visible at higher frequencies.

For the remote imaging scenario, we use WFS subapertures of either 25- or 6.7-mm diameter to measure the phase slope. Observing a variety of targets in sunlight, the slopes have no appreciable noise even down to exposures as short as 0.1 ms. Using a point source, we characterized the temporal PSDs of the WFS slopes for short horizontal paths. The PSDs follow a negative power law, with slight variations in exact structure depending on conditions. We have measured the slopes using Correlation on scenes and have obtained the same PSD structure and total level of power. This is experimental evidence that we can use Correlation with a scene as the WFS method in this scenario.

We have characterized the atmospheric coherence length over many trials, with results for a 100-m path clustering between 10 and 15 mm. Our results indicate that if our subapertures or field of view are too large, anisoplanatism will cause small parts of the scene to be shifted in different directions. Since Correlation assumes the entire scene is shifted in the same direction, this will prevent the successful use of Correlation. A target scene which clearly demonstrates this phenomenon for the 25-mm subaperture case is shown in Fig. 3.

Related References

1. Poyneer, L. A., "Scene-Based Shack-Hartmann Wavefront Sensing: Analysis and Simulation," *Applied Optics,* **42**, pp. 5807–5815, October 2003.
2. Poyneer, L. A., K. La Fortune, and C. Chan, "Scene-Based Wavefront Sensing for Remote Imaging," in *SPIE 5162 Advanced Wavefront Control: Methods, Devices, and Applications,* J. D. Gonglewski, M. A. Vorontsov, and M. T. Gruneisen, Eds., pp. 91–102, 2003.

FY2005 Proposed Work

We will continue our experimental work in the remote imaging scenario. We will use our experimental set-up to produce detailed system performance predictions for Correlation in comparison to established methods, such as speckle imaging and phase diversity. We will also experimentally verify the ability of Correlation to measure the aberrations on a lightweight nano-laminate optic.

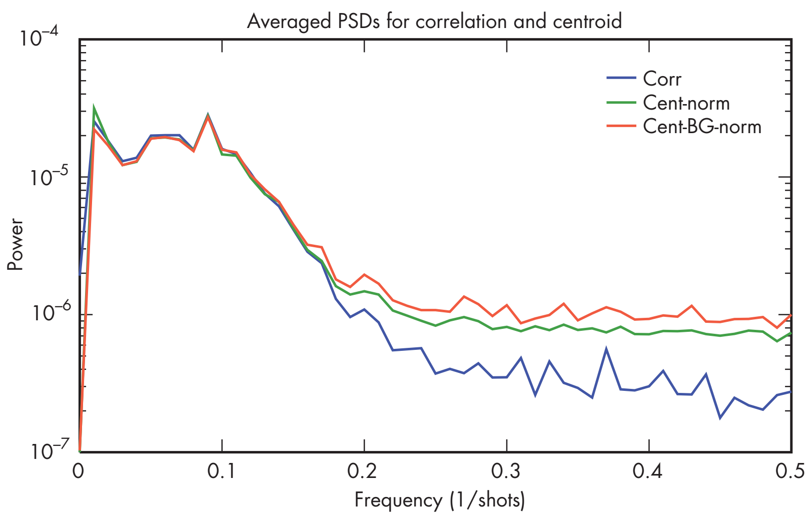

Figure 2. Temporal PSDs of open-loop WFS measurements for SSHCL.

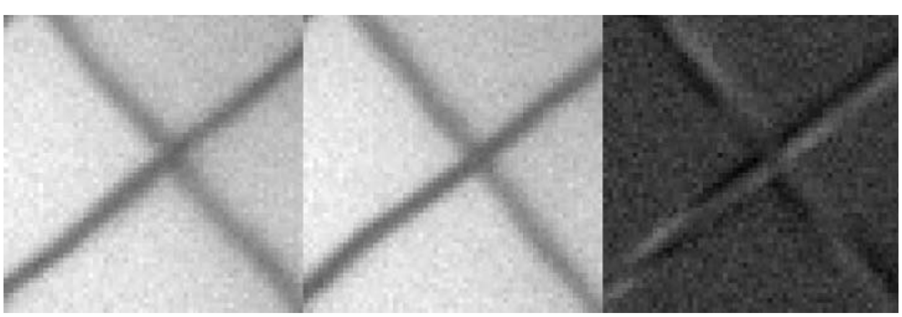

Figure 3. Sample scene demonstrating too-large subapertures and field of view. Shown are two sample subimages (a) and (b) from different points in time, and (c) the difference of these frames, clearly showing how different parts of the scene are deformed, as opposed to the entire scene shifted.